Detection of Extragalactic ^{15}N: Nitrogen Nucleosynthesis and Chemical Evolution

Christian Henkel[1], Yi-nan Chin[2,3], Norbert Langer[4], and Rainer Mauersberger[5]

1 Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany
2 Institute of Astronomy and Astrophysics, Academia Sinica, P.O.Box 1-87, Nankang, Taipei, Taiwan
3 Radiostronomisches Institut der Universität Bonn, Auf dem Hügel 71, D-53121 Bonn, Germany
4 Institut für Physik, Universität Potsdam, Am Neuen Palais 10, D-14469 Potsdam, Germany
5 Steward Observatory, The University of Arizona, Tucson, AZ 85721, U.S.A.

Abstract. Detections of extragalactic HC^{15}N are reported from the Large Magellanic Cloud (LMC) and the core of the (post-) starburst galaxy NGC 4945. The LMC data from the massive star-forming region N113 directly infer ^{14}N/^{15}N = 114 $\pm$ 14. For the LMC star-forming region N159 and for the central region of NGC 4945, the use of a 'reasonable' carbon isotope ratio (of order 50) also yields ^{14}N/^{15}N $\sim$ 100. These ratios are smaller than all interstellar nitrogen isotope ratios measured in the disk and center of the Milky Way, strongly supporting the idea that ^{15}N is synthesized by massive stars. Although contradicting standard stellar evolution and nucleosynthesis calculations, this supports recent findings of abundant ^{15}N production caused by rotationally induced mixing of protons into the helium burning shells of massive stars.

1 Introduction

Carbon, nitrogen, and oxygen, the 'CNO-elements', are among the most abundant species after hydrogen and helium. Being formed by p- and α-capture reactions in the interior of stars, CNO nuclei are released into the interstellar medium (ISM) by means of stellar winds, planetary nebula ejecta, and supernova explosions. While there exist many studies related to the main CNO species, the dominant cooking site of the rare nitrogen isotope, ^{15}N, is still controversial.

Observations indicate that ^{14}N production involves both a primary and a secondary component (e.g., Matteucci 1986; Vila-Costas & Edmunds 1993; van Zee et al. 1998). This is currently understood in terms of primary hydrostatic ^{14}N production in massive low metallicity stars (cf. Laird 1985, Timmes et al. 1995), while the secondary production of ^{14}N through the CNO cycle is dominating at higher metallicities (cf. Timmes et al. 1995; van den Hoek & Groenewegen 1997). Observationally, it has been shown that secondary nitrogen becomes dominant at [O/H] > –0.4 (e.g., Vila-Costas & Edmunds 1993).

^{15}N is destroyed during hydrostatic hydrogen-burning (e.g., Wannier et al. 1991; El Eid 1994; Langer & Henkel 1995) and is thus thought to be a product of explosive hydrogen nucleosynthesis. It is synthesized in novae as a mostly primary nucleus (e.g., José & Hernanz 1998). However, current models produce insufficient amounts to account for the galactic ^{15}N abundance (Kovetz & Prialnik 1997). Alternatively, it may be produced in Type II supernovae through neutrino spallation of primary ^{16}O (Timmes et al. 1995; Woosley & Weaver 1995; see also Audouze et al. 1977). A small contribution from Type Ia supernovae is also possible (Clayton et al. 1997; although see Nomoto et al. 1984). In the first case (novae), there is a time delay between star formation and the occurrence of ^{15}N enriched ejecta, leading to initially high ^{14}N/^{15}N ratios that gradually decrease with time (for an illustration, see e.g. Fig. 4 of Güsten & Ungerechts 1985). In the second case (massive stars), rapid injection of ^{15}N into the ISM leads to initially small ^{14}N/^{15}N ratios that gradually increase with time when the secondary ^{14}N contribution from low-mass stars becomes significant.

2 The ^{15}N puzzle

Analyzing interstellar ^{14}N/^{15}N data from HCN and NH_3, it soon became obvious that local ISM and galactic center ^{14}N/^{15}N ratios are moderately and strongly enhanced relative to the solar system value. If the solar system, the local ISM, and the galactic center region formed a sequence of increasing degree of nuclear processing, ^{15}N had to arise predominantly from massive stars (e.g., Audouze et al. 1977; Güsten & Ungerechts 1985). In this case we expect the more secondary ^{14}N nucleus to become more abundant relative to ^{15}N with higher metallicity, yielding ^{14}N/^{15}N ratios of 270, 300 – 400, and 500 – 1000 in the solar system, the local ISM, and the galactic center region, respectively (see Fig. 1).

The present 'nitrogen puzzle' is caused by two complications: Firstly, the Sun is more metal rich than the local ISM (e.g., Russell & Dopita 1992; Cameron 1993; Cunha & Lambert 1994; Meyer 1997), in spite of its age. This is still consistent with ^{15}N production in massive stars if we assume the Sun to be particularly enriched with nuclei processed in massive stars (e.g., Cameron 1993; Henkel & Mauersberger 1993). Secondly, Dahmen et al. (1995) found evidence favoring an interstellar galactic disk gradient with ^{14}N/^{15}N ratios (from HCN) increasing with galactocentric distance, opposite to what is expected from a short-lived stellar source rapidly injecting ^{15}N into the ISM (Matteucci & D'Antona 1991). Assuming instead delayed injection via novae fails to account for the large measured ^{14}N/^{15}N ratios in the galactic center region with its high number of potential nova candidates (e.g., Shafter 1997). The discrepancy between galactic disk and center nitrogen isotope ratios (favoring massive stars as the source of ^{15}N) is much more pronounced than the postulated ^{14}N/^{15}N gradient in the disk (favoring delayed ^{15}N enrichment from novae).

3 Extragalactic ^{15}N

Solving the nitrogen puzzle requires the determination of ^{14}N/^{15}N ratios in low metallicity and (post-) starburst environments containing gas that is strongly enriched by ejecta from massive stars (e.g., Henkel & Mauersberger 1993; Henkel

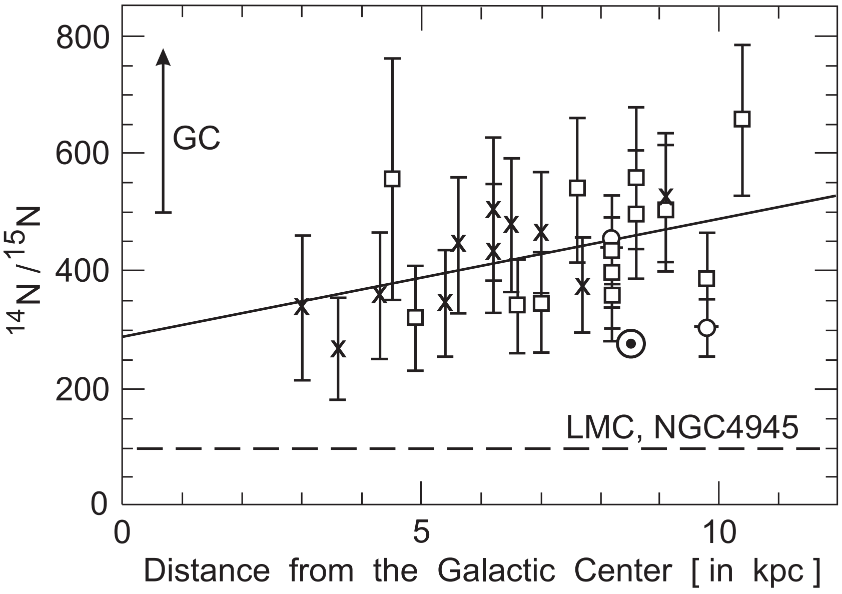

Fig. 1. The nitrogen isotope ratio as a function of galactocentric radius (for details, see Dahmen et al. 1995). The galactic center, LMC, NGC4945 and solar system values are also displayed.

et al. 1994). This can be done observing molecular clouds in various HCN isotopomers that reflect the actual ^{14}N/^{15}N ratio (see Chin et al. 1999 for details). A ^{14}N/^{15}N ratio of 114±14 was determined for the LMC star forming region N113 (Chin et al. 1999). This ratio is based on HCN and HC^{15}N J=1–0 ($\lambda \sim$ 4 mm) line intensities; the optical depth in the main line, HCN, was directly determined by a fit to its three hyperfine components. ^{14}N/^{15}N ratios for the LMC star forming region N159 and the nuclear region of NGC 4945 are less accurate because these are based on H^{13}CN and HC^{15}N data that require an a priori knowledge of the ^{12}C/^{13}C carbon isotope ratio. For 'reasonable' carbon isotope ratios of order 50, ^{14}N/^{15}N $\sim$ 100 (Chin et al. 1999; see Fig. 1).

4 Discussion

To check internal consistency, we now assume that ^{15}N is produced in massive stars. Then, ^{14}N/^{15}N ratios are smallest at low metallicities, where ^{14}N is also primary. At larger metallicities, i.e. [O/H] > –0,4, secondary ^{14}N begins to dominate, thus leading to ^{14}N/^{15}N isotope ratios that gradually rise with increasing metallicity. With [^{14}N/O] $\sim$ const. for primary and [^{14}N/O] $\propto$ [O/H] for secondary ^{14}N (e.g., Vila-Costas & Edmunds 1993), we then obtain for [O/H] $\geq$ –0.4

$$^{14}\mathrm{N}/^{15}\mathrm{N} = C \times\ 10^{[\mathrm{O/H}]\ +\ 0.4} \tag{1}$$

The quantity C, i.e. the initial isotope ratio, remains to be measured. The ISM of the LMC is less processed than the solar system and the local ISM and should be characterized by overabundances of nuclei ejected from massive stars. $[\mathrm{C/O}]_{\mathrm{LMC}} \sim [\mathrm{N/O}]_{\mathrm{LMC}} \sim -0.3$ is consistent with this hypothesis (e.g., Westerlund 1990). With [O/H] ~ -0.3 and ^{14}N/^{15}N = 114 $\pm$ 14 we then find $C \sim 100$. This infers ^{14}N/^{15}N $\sim$ 100 and 125 for the SMC and LMC, ^{14}N/^{15}N $\sim$ 200 for the local ISM ([O/H] ~ -0.1) and ratios of order 500 for the galactic center region ([O/H] $\sim$ 0.3; A. McWilliam, priv. comm.). The trend of rising nitrogen isotope ratios with oxygen abundance is consistent with our assumption that ^{15}N originates from massive stars. The resulting nitrogen isotope ratios for the galactic disk and center are, however, too small by a factor of almost two. A possible way to enhance galactic interstellar ^{14}N/^{15}N ratios to the values observed is to postulate some overall destruction of ^{15}N in low mass stars. This would address the combined ejecta of AGB stars and novae and is consistent with data from red giant stars (e.g., Wannier et al. 1991). Destruction of ^{15}N by long lived low mass stars in the LMC may be less pronounced if a significant part of its stellar population is young, being formed as a consequence of recent close encounters with the Galaxy (see e.g. Girardi et al. 1995; Elson et al. 1997; Holtzman et al. 1997; Geha et al. 1998).

If ^{15}N is released by high mass stars, an 'overabundance' of ^{15}N relative to ^{14}N is expected not only in galaxies with small metallicity, but also in more metal rich environments which are dominated by products of massive stars. The central region of the (post-) starburst galaxy NGC 4945 and, to a lesser degree, the solar system (possibly formed in an OB association) are suitable candidates. In the central region of M 82 with its still ongoing starburst, the nitrogen isotope ratio seems to be larger than in NGC 4945 (Henkel et al. 1998).

If ^{15}N would arise from novae, the small ^{14}N/^{15}N ratios in the LMC and NGC 4945 as well as the high ratios in the galactic center region would remain unexplained. *Our observational results from the LMC and NGC 4945 are thus providing strong support for ^{15}N being predominantly ejected by Type II supernovae.* This finding is not consistent with the sign of the galactic disk ^{14}N/^{15}N gradient (Dahmen et al. 1995; cf. Fig. 1)).

A production of ^{15}N is also not predicted by standard numerical calculations of massive star nucleosynthesis (e.g., Weaver & Woosley 1993). In fact, ^{15}N is efficiently destroyed in the CNO-cycle, i.e., during hydrogen burning in massive stars, and it is not produced in any of the later hydrostatic burning stages. Woosley & Weaver (1995) find a production of ^{15}N during the supernova explosion by neutrino spallation of (primary) ^{16}O. Even though the neutrino-process may turn massive stars into net producers of ^{15}N, the currently predicted amounts seem to be insufficient (by a factor of three) to account for the galactic ^{15}N (cf. also Timmes et al. 1995).

Recent explorations of the effects of rotation on the evolution and nucleosynthesis of massive stars (Heger et al. 1997, 1999, Langer et al. 1998) indicate the possibility of abundant hydrostatic production of ^{15}N in these objects. The rotation may cause internal turbulent motions which are otherwise absent, leading to nucleosynthesis processes in a mixture of hydrogen and helium burning products (Langer et al. 1999). Jorissen & Arnould (1989) have shown that such conditions may be favorable for ^{15}N production, and the yields found by Heger et al. (1999) and Langer et al. (1999) are consistent with a predominant production of the galactic ^{15}N in rotating massive stars. Consequently, although there are still considerable uncertainties and weakly restricted parameters in the rotating massive star models, massive stars should be considered as an important source of ^{15}N in galaxies.

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